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Bibliometric analysis and literature review on sustainable aviation fuel (SAF): Economic and management perspective

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ABSTRACT

Sustainable aviation fuel (SAF) is a key contributor to the aviation sector's efforts to achieve net-zero targets. This article presents a bibliometric analysis and literature review of 243 SAF-related publications from social science and quantitative disciplines, covering the period from 2014 to 2024. It highlights the latest research trends on the economic analysis of technological pathways, feedstocks, and policy interventions. Although SAF usage in commercial aviation is below 0.1% as of 2024, its decarbonisation potential could exceed 68%, particularly for medium- and long-haul flights. While biomass-based SAF faces constraints due to feedstock availability, the power-to-liquid pathway may offer a long-term solution. Five key themes have been identified in the literature: (1) sustainable certification of pathways and feedstocks, (2) economic simulations of alternative solutions, (3) economic feasibility of pathways and feedstocks, (4) supply chain dynamics and involvement of multiple stakeholders, and (5) policy interventions. Future studies could focus on economic simulations of airline competition under different SAF quotas, case studies on supply chain stakeholders, and the inclusion of grey literature for discussion. This research underscores the importance of international collaboration to create a level playing field for SAF adoption.

1. Introduction

While the International Civil Aviation Organization (ICAO) and the International Air Transport Association (IATA) commit to achieving net-zero emissions by 2050, national regulatory bodies, airlines, airports, and fuel suppliers are also joining this decarbonisation effort. Unlike the rapidly electrifying road transport, aviation is considered one of the few hard-to-abate industries, with limited options for reducing emissions. There are primarily two solutions: reducing the number of flights through voluntary passenger behaviour changes or higher ticket prices (via emissions taxes), and decreasing fossil fuel consumption through more efficient aircraft propulsion technologies and alternative fuels, particularly Sustainable Aviation Fuel (SAF) (Gössling and Dolnicar, 2023). However, with the rise of middle-income populations, especially in emerging economies like China, India, and ASEAN countries, and the global expansion of tourism, reducing air travel is becoming increasingly impractical. Achieving the 2050 carbon-neutral goal will require concerted efforts, including adopting new airplane designs, optimising air traffic routes for greater operational efficiency, and transitioning to SAF (Keiser et al., 2023).

Despite significant progress in enhancing aircraft operational efficiency, achieving further substantial gains proves challenging due to diminishing returns (Huang et al., 2023). While new aircraft designs and technologies have the potential to reduce aviation's carbon footprint, their large-scale implementation demands considerable time, investment, research, development, and certification (Abrantes et al., 2021; Barros Pintos et al., 2023; Yusaf et al., 2022). The futuristic electric and hydrogen-powered aircraft currently under development are primarily suited for short-haul routes (Eaton et al., 2023; Avogadro and Redondi, 2024). Hydrogen-powered aircraft are not expected to be commercialised before 2035 (Airbus, 2023), and the complete replacement of existing fleets will take even longer. Given these limitations, SAF has emerged as a vital short-to mid-term solution for decarbonising the aviation sector.

SAF is derived from renewable sources and has significantly lower, or even zero, life-cycle carbon intensity compared to traditional jet fuel. As

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a drop-in fuel, SAF can be blended with conventional jet fuel, requiring minimal or no modification to existing aircraft or infrastructure. This makes SAF a practical and scalable solution for decarbonising aviation while accommodating the growing demand for air travel. Hassan et al. (2018) found that large-scale SAF implementation could contribute to 64% of total emissions savings by 2050, compared to 31% from greener technologies and 5% from operational efficiency improvements.

However, widespread commercial adoption of SAF faces several barriers. Most notably, the current high cost of SAF discourages airlines from voluntary use. SAF is two to three times more expensive than conventional jet fuel (Ng et al., 2021), with recent prices around USD 2500 per tonne for SAF compared to USD 734 per tonne for conventional jet fuel (IATA, 2024b; IATA, 2024d).

To promote SAF adoption, governments are introducing regulations and offering financial subsidies. The European Parliament has approved a SAF mandate requiring at least 2% of aviation fuel to be SAF by 2025, increasing to 6% by 2030, 20% by 2035, and eventually 70% by 2050. Japan mandates that 10% of SAF be used for international flights departing from Japanese airports by 2030. Singapore plans to implement a SAF levy on departing flights, with a target of 1% in 2026, rising to 3–5% by 2030. The UK will implement its SAF mandate in 2025, starting at 2% of total jet fuel demand and increasing to 10% by 2030 (IATA, 2023a; IATA,2023b; IATA,2024d).

Several airlines have also voluntarily committed to SAF use. United Airlines has pledged to purchase up to 52.5 million gallons of SAF. The Lufthansa Group has partnered with OMV to supply over 800,000 tonnes of SAF from 2023 to 2030. Air France-KLM has signed contracts for 1.6 million tonnes of SAF with Neste and DG Fuels, while Delta Airlines has agreed to purchase 250 million gallons from Aemetis. American Airlines has finalised an agreement to buy 500 million gallons of SAF from Gevo. Emirates has conducted a demonstration flight using 100% SAF, and Singapore Airlines has signed an agreement with Neste for 1000 tonnes of SAF (Centre for Aviation Analysis Report, 2023). As of 2023, more than 50 airlines have used SAF on over 500,000 flights. Total SAF production by 2024 is expected to double from 2023 levels, reaching 1.5 million tonnes (Air France, 2023; CAPA, 2022a; CAPA, 2022b; CAPA, 2023a; S&P Global, 2022; S&P Global, 2024; Neste, 2023; OMV, 2023).

Sustainable aviation has become a prominent topic in academic discourse, as reflected in the growing number of reviews within the field. Afonso et al. (2023) conducted a systematic review of sustainable aviation strategies, covering not only fuel and propulsion systems but also operations, energy storage, aerodynamics, structures, materials, and manufacturing processes. Similarly, Su-ungkavatin et al. (2023) reviewed four key decarbonisation solutions for aviation: biofuels, electrofuels, battery-based electric propulsion, and hydrogen. Their review included nine biofuel and electrofuel pathways, five key battery technologies, and six existing and emerging carbon-free hydrogen production technologies.

Undavalli et al. (2023) examined recent advancements in SAF regarding operational performance, emissions impact, engine and fuel system compatibility, and other technical aspects. Heyne et al. (2021) laid important groundwork for prescreening procedures preceding the official ASTM D4054 certification process. Yusaf et al. (2022) and Mannava and Velautham (2023) endorsed hydrogen as an ultimate solution but acknowledged the challenges of scaling it up in the short term.

Regarding feedstocks, Wei et al. (2019) and Peters et al. (2023) reviewed the production technologies of biomass-derived SAF. Song et al. (2023) explored hydroprocessing of lipids, a feedstock for HEFA, the most mature and commercially viable pathway in terms of technology and fuel readiness (see also Watson et al., 2024). Emmanouilidou et al. (2023) reviewed SAF production from solid waste biomass. Zhang et al. (2020) published groundbreaking work by reviewing trends, opportunities, and challenges in SAF, discussing the market size in the US and globally, and providing detailed comparisons of feedstock and fuel characteristics, including the use of SAF in 18 commercial airline flights between 2008 and 2015. This work laid the foundation for future techno-economic analysis.

Chiaramonti (2019) was among the first to include market projections in discussions of SAF pathways and feedstocks. The US Department of Energy (2024) reviewed all technical SAF pathways, noting that sourcing iso-alkanes, cycloalkanes, and high-performing molecules from low-cost resources is key to production, alongside the social and environmental benefits of SAF derived from wastes. Doliente et al. (2020) compared techno-economic analyses of various generations of feedstocks, addressing emissions, costs, storage, and transport challenges. The ideal feedstock and technology depend on spatial and temporal factors. Shahriar and Khanal (2022) and Cabrera and de Sousa (2022) explored existing techno-economic analyses and examined policy initiatives incentivising SAF production and adoption. Grimme (2023) and Braun et al. (2024) contributed reviews on SAF production costs and minimum selling prices. Further reviews by Ng et al. (2021) and Wang et al. (2024) focused on market potential and specific technological production processes for each pathway.

Watson et al. (2024) advanced previous research by extracting techno-economic (TEA) and life cycle analysis (LCA) data from over 50 sources, presenting a comprehensive overview of SAF technologies, costs, emissions profiles, and policy implications. They are among the few to propose four macro-level future research directions related to economics, management, and policy: a realistic roadmap to 2050, prospects beyond 2050, standardised guidelines for TEA and LCA, and their integration into policymaking.

Despite a substantial body of technological knowledge accumulated in recent years, non-engineering aspects, including economic viability, the impact on airline competition, and the role of government in stimulating production and adoption, have received little attention. This bibliometric analysis and systematic literature review (SLR) focus on the economic, policy, and managerial aspects, aiming to identify themes that encourage greater participation from social sciences in this critical discussion and to elaborate future research directions. Bibliometric analysis could complement and enhance the traditional systematic literature review by providing insights into research trends, academic networks, and citation patterns, allowing researchers to track the most influential and relevant studies on SAF and map interdisciplinary connections. A total of 1378 related journal articles published between 2014 and 2024 have been collected and analysed.

This paper finds that biomass-derived SAF is constrained by feedstock availability, but the Power-to-Liquid pathway may offer a long-term solution. Five key themes have emerged in the literature: (1) sustainable certification of pathways and feedstocks, (2) economic simulations of alternative solutions, (3) economic feasibility of pathways and feedstocks, (4) supply chain dynamics and involvement of multiple stakeholders, and (5) policy interventions. Future studies may focus on economic simulations of airline competition under different SAF quotas and case studies on supply chain stakeholders. This research underscores the importance of international collaboration to create a level playing field for SAF adoption and calls for research on multiple stakeholders across the SAF supply chain, the potential impacts of airline alliances and air passengers on airlines, along with their ripple effects on competition. Additionally, it highlights the importance of engaging with grey literature, which is evolving rapidly and offering timely updates.

The remainder of this article is structured as follows: Section 2 is dedicated to methodology, Section 3 summarises the results of the bibliometric analysis and SLR, Section 4 discusses the themes identified in the existing SAF literature, and Section 5 concludes by offering future research directions on SAF.

2. Methodology

A systematic literature review (SLR) follows a structured approach to identify literature relevant to specific research questions (Tranfield et al., 2003). This SLR adhered to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (2021

update). The PRISMA framework was used to identify, screen, and select articles for inclusion in the review and bibliometric analysis, with the assistance of Bibliometrix and VOSviewer. Bibliometrix, an R package, supports co-citation, coupling, and co-word analysis, making it a powerful tool for scientometric research (Aria and Cuccurullo, 2017). VOSviewer offers text-mining functionality to visualise co-occurrence networks of key terms in scientific literature (Van Eck and Waltman, 2010; Radha and Arumugam, 2021; Liu et al., 2024).

Although sustainable aviation fuel is the main keyword, there are also synonyms widely used due to different conventions. The search query TITLE-ABS-KEY ("sustainable aviation fuel" OR "sustainable jet fuel" OR "renewable aviation fuel" OR "renewable jet fuel" OR "alternative aviation fuel" OR "alternative jet fuel" OR "bio aviation fuel" OR "bio jet fuel" OR "aviation biofuel" OR "jet biofuel" OR "synthetic aviation fuel" OR "synthetic jet fuel") was applied to English-only journal articles and reviews from 2014 to 2024. The initial search found 1361 articles from the Scopus database and 1123 from the Web of Science Core Collection (WoS Core), yielding a total of 2484 articles (as of September 17, 2024). After removing duplicates, 1378 articles remained.

The research on SAF encompasses both natural and applied sciences, notably chemical engineering and biological science, as well as social sciences and qualitative disciplines. A filter of subject areas was also applied. By selecting the subject areas of Scopus and WoS, categories in 'natural and applied sciences'—including energy, chemical engineering, environmental science, chemistry, engineering, agricultural and biological science, physics, biochemistry, material sciences, microbiology, and earth science—generated 1330 results. Categories in 'social sciences and quantitative disciplines'—including social science, economics, econometrics and finance, business, management and accounting, and decision sciences—generated 243 results. There is some unavoidable overlap between the two categories due to the multidisciplinary nature of the topic, such as the techno-economic analysis of the Alcohol-to-Jet pathway.

PRISMA is commonly followed by thematic identification; however, given the high volume of literature, using Braun and Clarke's six-step thematic analysis could complement semantic analysis (Braun and Clarke, 2006). Semantic analysis can help clarify and refine themes by examining the language used in the data and validating the identified themes, ensuring they truly represent the data (Liu et al., 2024). Because understanding the 'natural and applied sciences' is the prerequisite for this alternative jet fuel discussion, a brief overview will be provided, followed by an analysis focusing on managerial and policy implications, which are generally lacking in the existing literature on SAF. The aim is to engage economic, management, and policy researchers in the conversation on aviation decarbonisation (Fig. 1).

3. Results

3.1. Leading sources and authors

From 2014 to 2017, the trend in the number of articles produced each year remained relatively stable. However, from 2018 to 2020, publications doubled, and both categories experienced a dramatic increase after 2021. The category 'natural and applied sciences' is denoted as (n), while 'social sciences and quantitative disciplines' is denoted as (s) in Fig. 2.

For the 'natural and applied sciences' categories, the majority of sources are from the journal Fuel (134 articles in the last decade), followed by related energy publications. Most of these articles were published in Fuel between 2021 and 2022 (in Fig. 3). 'Heyne, Joshua' and 'Washington State University' are the most frequent author and affiliation in SAF research, based on the number of articles produced (Table 1).

For the social sciences and quantitative disciplines, the leading authors are Uwe Riedel and Wei-Cheng Wang, affiliated with the Institute of Combustion Technology and Beihang University (Table 2). Four clusters of authors exist in this field, with Heyne, Joshua and Yang, Zhibin from the U.S. among the most relevant authors leading their cluster (Fig. 4).

The most cited sources include Energies, Frontiers in Energy Research, and Journal of Cleaner Production (Fig. 5). These interdisciplinary journals primarily focus on applied science, suggesting that the existing discussions of specific SAF policies base on a solid understanding of established knowledge regarding technological production pathways, chemical properties, and industrial development.

The Journal of Air Transport Management, Energy Economics, Transportation Research Part A, and Transport Policy are closely connected with Frontiers in Energy Research and Journal of Cleaner Production, but contribute less than journals like Energies. Articles in the Journal of Air Transport Management, Energy Economics, and Transport Policy were published before 2022, while articles in Transportation Research Part A have generally weaker interrelatedness compared to those in Fig. 3 (using the same parameters with min. strength 15 and max. lines 100). This is due to the lesser inter-citations and references among these journals, indicating that social science research on SAF remains siloed.

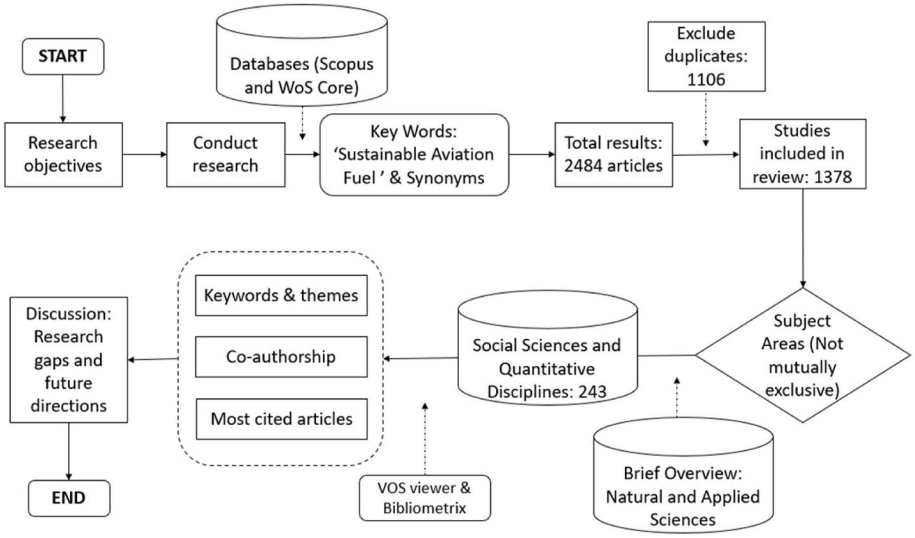

Fig. 1. Flowchart illustrating the review procedure.

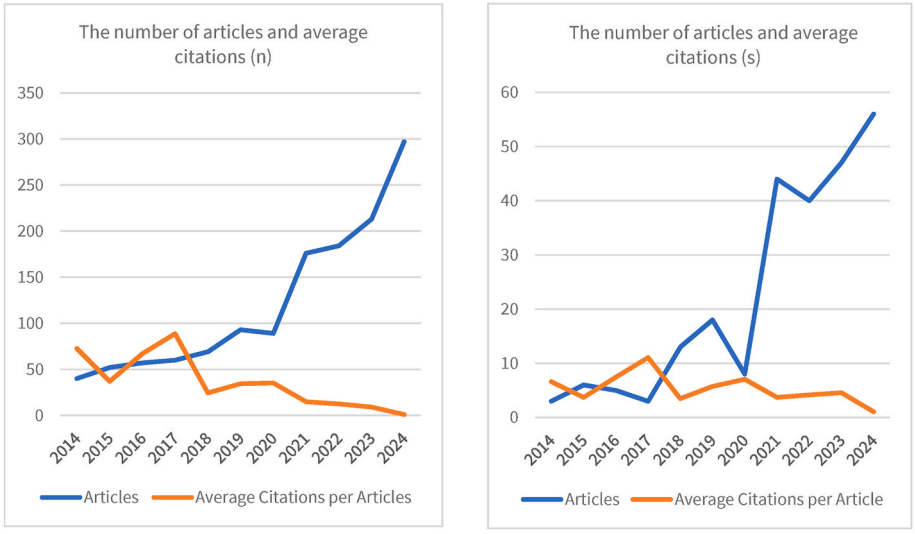

Fig. 2. The number of articles and average citations (Left: natural and applied sciences; Right: social sciences and quantitative disciplines).

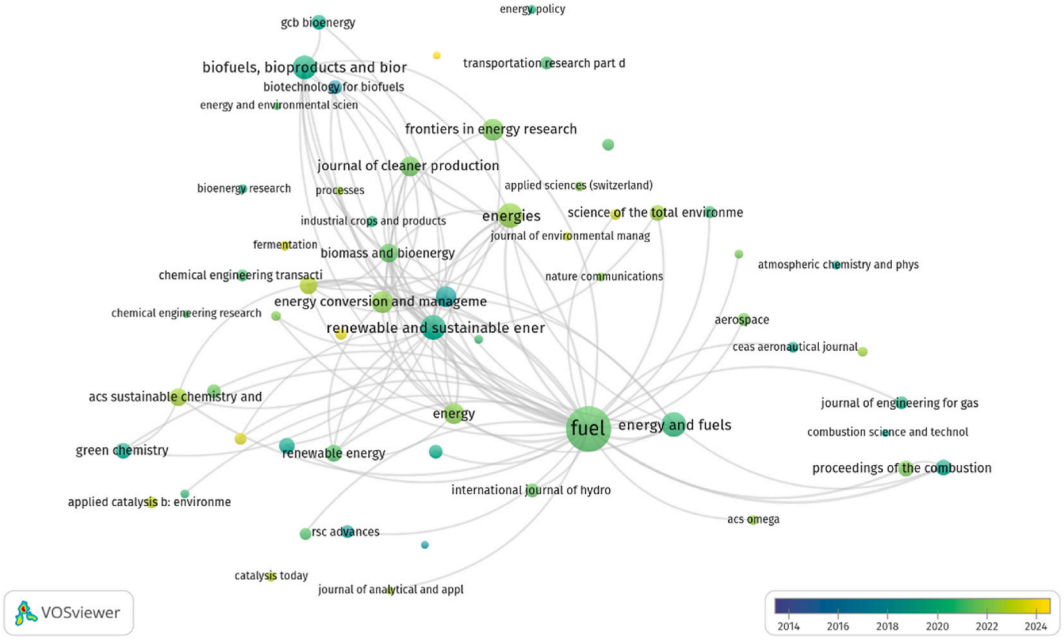

Fig. 3. The co-occurrence network for sources in 'natural and applied sciences'.

3.2. Semantic analysis and refining themes

A visual summary of frequently used words reveals trends and patterns that warrant further investigation. By removing synonyms of 'Sustainable aviation fuel', which contribute significantly to the keyword word cloud as they are commonly searched queries, we can better highlight the key terms in the articles.

The overall word cloud derived from the keywords (Fig. 6) provides interesting insights into current research across both natural and applied sciences, including fatty acids, pyrolysis, Fischer-Tropsch processes, engines, and hydrocarbons, as well as social sciences such as economic analysis, air transportation, supply chain, and the aviation sector. However, a co-occurrence network analysis (Fig. 7) further elucidates the semantics.

In this network, three clusters of highly shared keywords were identified. The green cluster, which includes economic analysis, supply chain, cost-benefit analysis, and oilseeds, focuses on feedstock and its economic implications. The red cluster encompasses keywords related to the airline industry, air transportation, civil aviation, sustainability, climate change, and emission control, reflecting macro discussions on aviation decarbonisation policy design. The blue cluster is weaker than the others, comprising keywords such as hydrocarbons, kerosene, combustion, blending, and engines, which relate to certification regulations for fuels.

Most articles using these keywords were published in 2021 and 2022 (Fig. 8). The relationships between different concepts were analysed to identify clusters of related terms, providing insights into main themes and emerging trends. Complemented by the aforementioned semantic

Table 1
Most frequent authors and affiliations in 'natural and applied sciences'.

Authors	Articles	Affiliation	Articles
HEYNE, JOSHUA	28	WASHINGTON STATE UNIVERSITY	195
WANG, WEI-CHENG	22	INSTITUTE OF COMBUSTION TECHNOLOGY	146
GUTIÉRREZ-ANTONIO, CLAUDIA	18	BEIHANG UNIVERSITY	138
WOLCOTT, MICHAEL	18	PURDUE UNIVERSITY	109
YANG, XIAOYI	15	ZHEJIANG UNIVERSITY	108
GARCIA-PEREZ, MANUEL	14	TIANJIN UNIVERSITY	81
GÓMEZ-CASTRO, FERNANDO ISRAEL	14	DALIAN INSTITUTE OF CHEMICAL PHYSICS	67
HARVEY, BENJAMIN G.	14	GUANGZHOU INSTITUTE OF ENERGY CONVERSION	65
HERNÁNDEZ, SALVADOR	14	SOUTHEAST UNIVERSITY	65
KILAZ, GOZDEM	14	UNIVERSITY OF SCIENCE AND TECHNOLOGY OF CHINA	62

Table 2
Most frequent authors and affiliations in 'social sciences and quantitative disciplines'.

Authors	Articles	Affiliation	Articles
RIEDEL, UWE	7	INSTITUTE OF COMBUSTION TECHNOLOGY	33
WANG, WEI-CHENG	7	BEIHANG UNIVERSITY	32
BRAUN-UNKHOFF, MARINA	6	WASHINGTON STATE UNIVERSITY	31
HEYNE, JOSHUA S.	6	SOUTHEAST UNIVERSITY	25
ENGLISH, BURTON C.	5	PURDUE UNIVERSITY	22
JASIŃSKI, REMIGIUSZ	5	NATIONAL CHENG KUNG UNIVERSITY	17
WOLCOTT, MICHAEL	5	CATALYTIC CARBON TRANSFORMATION CENTER	16
BRANDT, KRISTIN	4	UNIVERSITY OF CALIFORNIA	15
DWIVEDI, PUNEET	4	UNIVERSITY OF TENNESSEE	15
KARAMI, OMID	4	UNIVERSITY OF DAYTON	14

analysis, Braun and Clarke's six-step thematic analysis was employed, which includes: familiarising with the data, generating initial codes, searching for themes, reviewing themes, defining themes, and writing up. This process refined five key themes: (1) sustainable certification of pathways and feedstocks, (2) economic simulation of alternative solutions, (3) economic feasibility of pathways and feedstocks, (4) supply chain dynamics and involvement of multiple stakeholders, and (5) policy interventions.

4. Discussion of the key research themes

4.1. Sustainable certification of pathways and feedstocks

The potential of using SAF to decarbonise the aviation sector has been supported by many studies (Prussi et al., 2019; Rupcic et al., 2023; Smith et al., 2017; Wang et al., 2023a; Wang et al., 2023b). It is estimated that a reduction of approximately 68% could be achieved by 2050 if over 85% of aviation fuel demand is met with SAF (Staples et al., 2018; Hamdan et al., 2022). However, the availability of SAF is constrained by limited feedstocks and pathways, along with strong demands from multiple transport sectors (Urban et al., 2024). The source of feedstock is crucial, as it directly impacts the sustainability and scalability of the SAF production process. The first key theme explores optimal pathways and suitable feedstocks.

Currently, there are eight certified pathways and two co-processing pathways, as shown in Table 3. HEFA is the most commercially mature pathway in use today, followed by Fischer-Tropsch and Alcohol-to-Jet (BP, 2024) (see Table 4).

Lipids, found in used cooking oil, waste grease, animal fats, plant oils, and microalgae oils (Doliente et al., 2020), are accessible and market-mature feedstocks, particularly for the HEFA pathway. Much research has focused on identifying new oil sources, with cover crops such as pennycress, carinata, and camelina among the most discussed (Taheripour et al., 2022; Phippen et al., 2022; Mousavi-Avval et al., 2023; Alam and Dwivedi, 2019; Karami et al., 2022; Field et al., 2022). Other noteworthy sources include jatropha oil, babassu oil, palm oil, tamanu oil, sunflower oil, and rubber seed oil (Baidoo et al., 2022; Cican et al., 2023; Hamdan et al., 2022). Food waste could also serve as an oil source, although controlled fermentation to produce volatile fatty acids (VFA) comes at a relatively high cost (Huq et al., 2021; Darda et al., 2019).

Lignocellulosic biomass is another potential feedstock. Lignin-derived jet fuel could enhance the economic viability of SAF due to low-cost production, high thermal stability and energy density, and low greenhouse gas emissions (Ahmad et al., 2021; Hamdan et al., 2022). Large amounts of woody residues (e.g., wood chips and sawdust) from Sweden, Finland, and Norway (Siegfried et al., 2023; Puschnigg et al., 2023; Cavalett and Cherubini, 2018), forest residue in the central Appalachian region of the U.S. (English et al., 2022), and cellulosic biomass

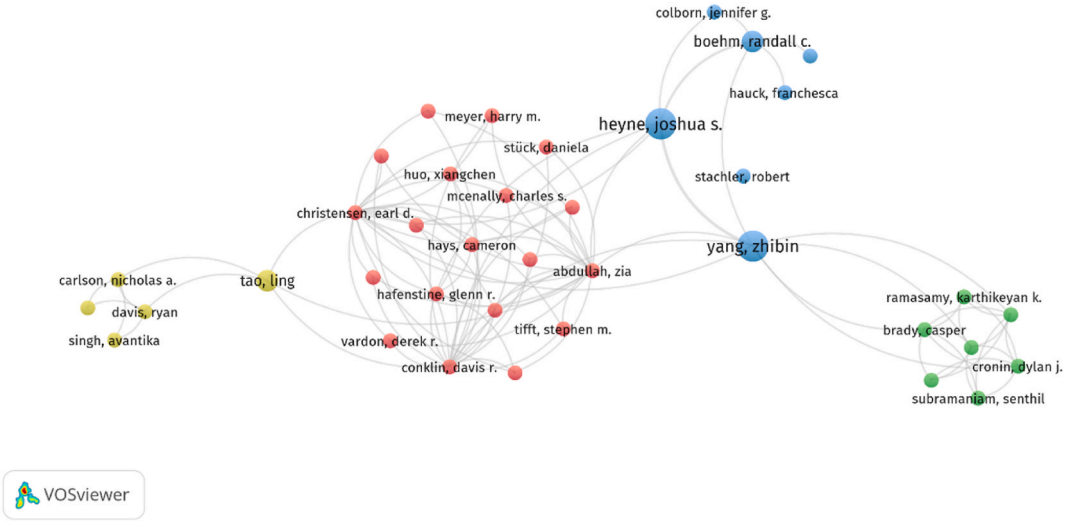

Fig. 4. The co-authorship network in 'social sciences and quantitative disciplines'.

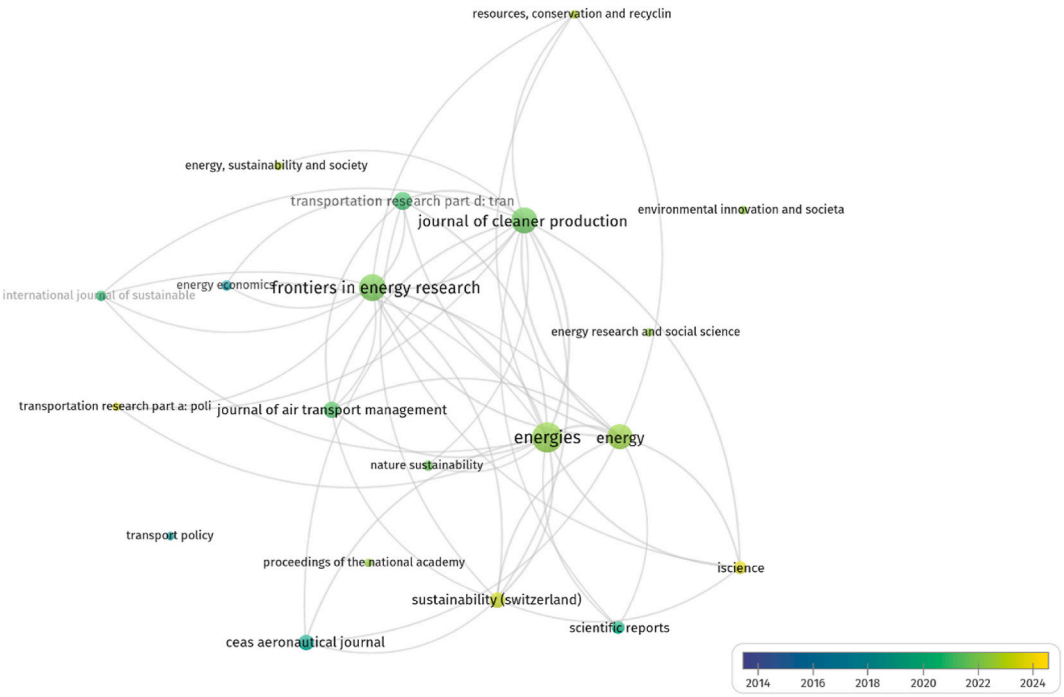

Fig. 5. The co-occurrence network for sources in 'social sciences and quantitative disciplines'.

Fig. 6. A word cloud of keywords in the articles in 'social sciences and quantitative disciplines'.

such as miscanthus, sorghum, or switchgrass are of scholarly interest (Gautam et al., 2023; Uludere Aragon et al., 2023). However, lignocellulosic SAF technologies face a significant limitation—low fuel yields—primarily due to the high oxygen content of the feedstock. The gasification and Fischer–Tropsch processes may offer advantages in maximising fuel yield (Tanzil et al., 2021; Krogh et al., 2022; Rijo et al., 2023).

Ethanol, waste gases, green hydrogen, and captured carbon are potential feedstocks (Martini et al., 2018; Ahmad et al., 2021; Collis et al., 2022; Micheli et al., 2022). However, each faces specific challenges. While alcohols, particularly ethanol, are commonly used in vehicles either as pure ethanol or blended with petrol, they may not be suitable for direct use in aircraft engines and require conversion via the AtJ process. In São Paulo, Brazil, researchers have identified sugarcane as a viable feedstock for the local subindustry; however, the lack of sustainability safeguards on sugarcane cultivation raises concerns regarding land use and food competition (Martini et al., 2018). Steel mill gases, coke oven gas, and blast furnace gas can be used as feedstocks for the FT process (Ahmad et al., 2021), but the high cost of carbon capture and storage (CCS) means waste gases would only be feasible under a high carbon tax regime (Collis et al., 2022). Using electrolysis to produce hydrogen is also costly, similar to CCS. Green hydrogen, generated from renewable power, is currently more efficiently used directly than converted to SAF via the FT pathway (Micheli et al., 2022).

The articles on this theme of pathways and feedstocks lay a solid foundation for the extended literature discussion.

4.2. *Economic simulation of alternative solutions*

Given the constraints facing the production and adoption of SAF, researchers have conducted economic simulations of non-SAF strategies to achieve the 2050 net zero goal. Kito et al. (2023) compared two pathways using data from Japan. One pathway relies on established methods (non-future technology), such as gradually improving fuel efficiency, controlling flight distance, and extending aircraft lifetimes. The other pathway considers less predictable methods (future technology), such as introducing SAF. The non-future technology pathway demonstrated that suppressing cumulative flight distances by at least 27% by 2050 could help achieve carbon neutrality, assuming maximised fuel efficiency and aircraft lifetimes, replacing domestic flights with rail transport, limiting international leisure flights, and increasing fares by up to 48% to compensate for sales declines.

Sobieralski (2023) found that operational efficiency increased with an improved Flight Management System (FMS), which includes a social cost index metric to optimise speed. Implementing this index could save approximately 22 gallons of jet fuel per flight per hour, with potential

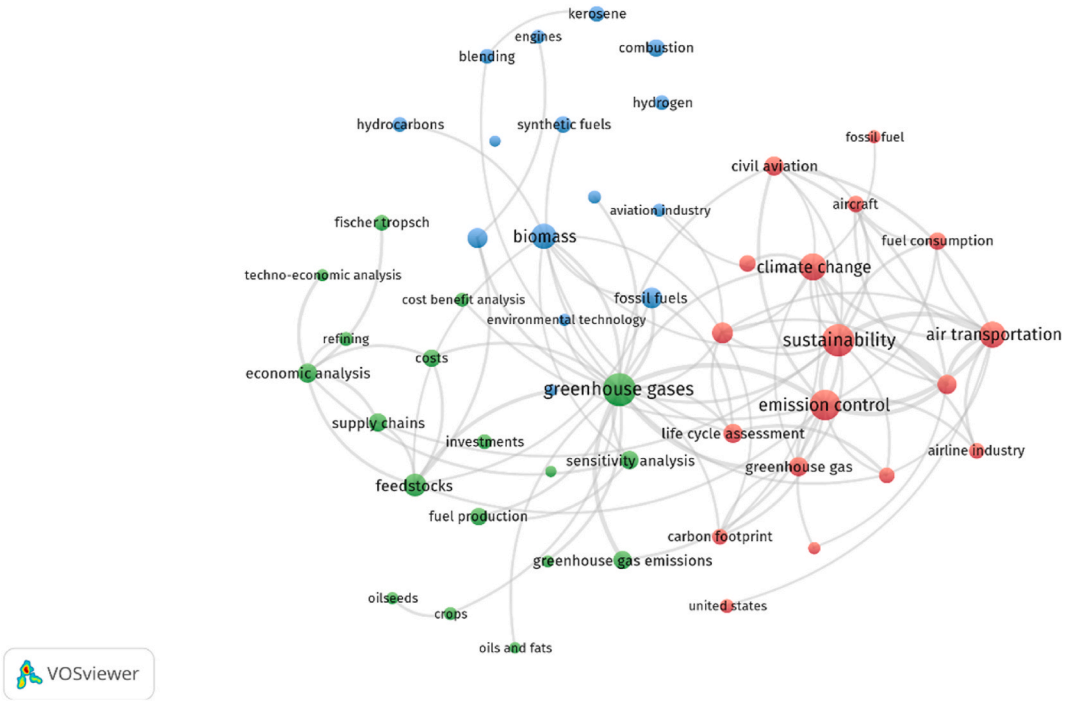

Fig. 7. Co-occurrence clustered network for keywords in 'social sciences and quantitative disciplines'.

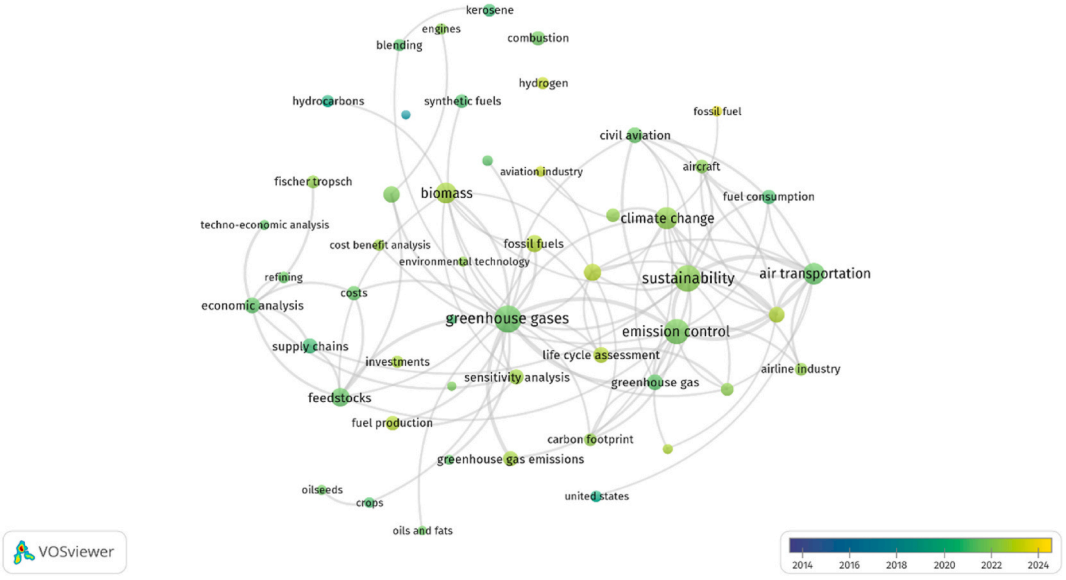

Fig. 8. Co-occurrence time-laying network for keywords in 'social sciences and quantitative disciplines'.

savings including a 7%–23% reduction in fuel burn compared to traditional climbs and a 10%–28% reduction in noise. However, Villegas Díaz et al. (2020) noted that enforcing optimal continuous climb operations is challenging due to varying contexts. While the numbers appear promising, the cumulative effect of improved flight operational efficiency contributes minimally. For example, in China's commercial aviation sector, CO2 emission reductions from flight operational improvements were only 2.11 Mt between 2009 and 2019, due to increasing travel demand and lagging technological advancements. Under the baseline scenario, aviation carbon intensity could achieve a maximum reduction of 65% by 2035 and even less by 2050 (Huang et al., 2023).

Redesigning aircraft has the potential to increase efficiency even with conventional jet fuel. Abrantes et al. (2021) found that new engines and wing designs could reduce emissions by up to 15% by 2050. Hydrogen and electricity are viable for short-haul flights in the near term. Electric propulsion eliminates water vapour and other greenhouse gases (GHGs) and reduces noise both inside and around aircraft. However, fully electric aircraft are feasible only for distances of up to 250–300 km. Liquid hydrogen is preferred, offering an 83% reduction in emissions with a minimal weight increase of 0.5%. While hydrogen-powered flights could reach up to 2900 km under optimal scenarios, this option requires dedicated infrastructure for hydrogen storage and transfer at airports (Barros Pintos, 2023).

Hydrogen may be the ultimate solution for the future. However, before 2050, the volumetric size of liquid hydrogen presents a significant concern regarding compatibility with existing engines and aircraft.

Table 3
Certified SAF pathways.

ASTM D7566-23b Annex	Certified SAF	Maximum Blend (%v/v)	Approval year	Feedstocks
Annex A1	Fischer-Tropsch Synthetic Paraffinic Kerosene (FT-SPK)	50	2009	Syngas, a mixture of CO and H2, produced from the gasification of biomass such as agricultural and forest wastes, municipal solid waste, wood and energy crops, or coal and natural gas.
Annex A2	Hydroprocessed Esters and Fatty Acids Synthetic Paraffinic Kerosene (HEFA-SPK)	50	2011	Triglyceride feedstocks including animal and plant oil, yellow or brown greases, or waste fat, oil, and greases.
Annex A3	Hydroprocessed Fermented Sugars to Synthesised Iso-Paraffins (HFS-SIP)	10	2014	Microbial conversion of sugars to hydrocarbons. Feedstocks include cellulosic biomass feedstocks such as herbaceous biomass and corn stover, pretreated waste fat, oil, and greases.
Annex A4	Fischer-Tropsch Synthetic Paraffinic Kerosene with Aromatics (FT-SPK/A)	50	2015	Like FT-SPK ASTM D7566 Annex A1, but with the addition of aromatic components.
Annex A5	Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ, isobutanol)	50	2016	Ethanol and isobutanol produced from lignocellulosic biomass (e.g., corn stover).
Annex A5	Alcohol to Jet Synthetic Paraffinic Kerosene (ATJ, ethanol)	50	2018	ASTM approved in April 2016 for isobutanol and in June 2018 for ethanol with a 30% blend limit.
Annex A6	Catalytic Hydrothermolysis Synthesised Kerosene (CHJ or CH-SK)	50	2020	Triglyceride-based feedstocks such as soybean oil, jatropha oil, camelina oil, carinata oil, and tung oil.
Annex A7	Hydroprocessed Hydrocarbons, Esters and Fatty Acids Synthetic Paraffinic Kerosene (HC-HEFA-SPK)	10	2020	*Botryococcus braunii*, a high-growth algae that produces triglyceride oil.
Annex A8	Alcohol to Jet Synthetic Kerosene with Aromatics (ATJ-SKA)	50	2023	Like FT-SPK ASTM D7566 Annex A5, but with the addition of aromatic components.
ASTM D1655-23 Annex	**Certified SAF**	**Maximum Blend (%v/v)**	**Approval date**	**Feedstocks**
Annex A1	Co-Processing	5%		Fats, oils and greases or Fischer-Tropsch biocrude

Note: Complied by the authors from the following sources: ASTM International (2023); Aviation Benefits (2024); CAAFI (2024); IATA (2024a).; ICAO (2024); SkyNRG (2024a); SkyNRG (2024b) The U.S. Department of Energy (2024). These forms are for reference only; all engineering, chemical, and relevant details have been simplified. Please refer to the original ASTM documentation for more information.

Introducing entirely new designs may result in daunting upfront costs for manufacturers and operators (Yusaf, 2022), which many airlines cannot afford given the industry's thin profit margins.

While the production and adoption of SAF face numerous obstacles, Mayeres et al. (2023) found that an emissions trading scheme could be a low-hanging fruit. Their techno-economic model indicated that a tax on fossil fuel incurs a lower welfare cost per tonne of GHG abated compared to both a blending mandate and a SAF subsidy. Consequently, emissions trading schemes (ETS), such as the EU-ETS and the Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA), are more cost-effective. This is because the sectoral source is less relevant, as some sectors can reduce GHG emissions more easily than others. Proost (2024) used a model to verify that the EU-ETS is the most stable and robust pathway for the EU to achieve net zero, complemented by SAF research and development incentives, while the SAF mandate is the least efficient to kickstart SAF adoption.

4.3. Economic feasibility of pathways and feedstocks

SAF is currently not an economically viable option for airlines, as it is approximately 3.5 times more expensive than Jet A1 fuel (Watson et al., 2024). The recent average price of SAF from various sources is around US$2437 per tonne (IATA, 2024b), compared to about US$690 per tonne for Jet A1 (Jet-A1-Fuel, 2024). This gap widens further in the absence of a carbon trading market. However, efforts are being made to make SAF economically sustainable. According to Watson et al. (2024), the HEFA pathway, the most mature market option, offers comparatively lower costs than Fischer-Tropsch, AtJ, and CHJ. Research indicates that the minimum sustainable price (MSP) of HEFA derived from inedible fats and oils is US$1100 per tonne, while HEFA from palm fatty acid distillate and ATJ from corn grain have MSPs of US$1400 per tonne (Wang et al., 2021). However, the limited availability of lipid feedstock makes the HEFA pathway unsustainable for achieving 2050 goals if relied upon solely (Yilmaz, 2022; Cui and Chen, 2024; Collis et al., 2022).

The upfront costs and operational expenses of biorefineries, along with the logistical challenges of producing, transporting, and storing SAF, further affect its economic feasibility. For instance, the capital cost of a HEFA production plant using rubber seed oil is US$8.7 million, with an annual operating cost of US$0.33 million (Baidoo et al., 2022). Strategies such as establishing a book-and-claim mechanism, optimising transport to the nearest airport, and strategically locating biorefineries can mitigate costs and emissions (Doliente et al., 2020; Mousavi-Avval et al., 2023). Maximum prices paid to farmers for feedstock like Pennycress range from 10.18 to 11.73 cents per pound, equivalent to US $225 to US$259 per tonne. These prices are closely linked to farmers' willingness to adopt oilseed plants (Trejo-Pech et al., 2021; McCollum et al., 2021), highlighting the need for concerted efforts to reduce SAF prices to sustainable levels.

There is ongoing debate about safety concerns and their long-term financial implications for the widespread deployment of SAF. Studies (Kramer et al., 2022; Babuder et al., 2024) suggest that more frequent safety inspections may be required for relevant aircraft components (e.g., fuel systems) and airport operations (e.g., re-fuelling systems). However, other research indicates that the variability of SAF is negligible, allowing for widespread adoption without major changes to engines or infrastructure (Oldani et al., 2022). This aligns with findings that within blend limits, the use of SAF is not expected to significantly

Table 4
The average performance of each technology's MSP and CO2 emissions compared to conventional jet fuel.

Technology	MSP Average (USD per Liter)	USD per Tonne	Percent Increase from Conventional	CO2 Emissions Average (gCO2eq MJ−1)	Percent Decrease from Conventional
FT-SPK	2.08	2540	320%	7.84	92%
HEFA-SPK	1.12	1370	120%	65.22	27%
ATJ-SPK	1.69	2060	240%	38.67	57%
HFS–SIP	3.99	4870	700%	42.02	53%
CHJ-SPK	1.3	1590	160%	20.58	77%

Source: Watson et al. (2024).

impact operations (Babuder et al., 2024; Barros Pintos et al., 2023; Cican et al., 2023).

Extensive research has examined the impact of technological pathways, feedstocks, biorefinery costs, logistics, maximum feedstock prices, and additional labour costs for safety checks on SAF production (Babuder et al., 2024; Baidoo et al., 2022; Barros Pintos et al., 2023; Cican et al., 2023; Collis et al., 2022; Cui and Chen, 2024; Doliente et al., 2020; Kramer et al., 2022; McCollum et al., 2021; Mousavi-Avval et al., 2023; Oldani et al., 2022; Trejo-Pech et al., 2021; Yilmaz, 2022). Future research should prioritise developing a standardised reporting format for SAF production costs, including both simulation and actual production data. There are currently limited reports on initial and operational costs associated with standalone or co-processing biorefineries, logistical expenses, and additional labour costs for safety checks. The maximum purchasing price of feedstock also remains underreported. This highlights the need for a standardised reporting format to facilitate monitoring fluctuations and gaps, enhancing transparency, efficiency, and economic viability within the SAF production landscape.

4.4. Supply chain dynamics and involvement of multiple stakeholders

The existing literature identifies that the supply chain of SAF comprises five phases plus logistical transport (rail, truck, or pipeline) connecting them: feedstock production, feedstock processing, refining and certification, blending and certification, and fuelling and end-use (BP, 2024; CSIRO, 2023; IATA, 2024c; SkyNRG, 2024a; SkyNRG, 2024b). For each phase of the SAF supply chain, highly trained professionals are required to manage the new challenges in accordance with updated SAF guidelines. The first phase involves cultivating or collecting feedstock for preprocessing. The second phase entails initial treatment (e.g., biochemical and thermochemical processes) of raw feedstock to produce intermediate products. The third phase converts these intermediate products into final SAF via certified technological pathways and certifies them according to ASTM D7566. Given that only a limited percentage of SAF can be used at this stage, the fourth phase blends pure SAF with conventional Jet A/A-1 fuel, requiring additional certification to ensure compliance with ASTM D7566 standards (Martinez-Valencia et al., 2023; Phippen et al., 2022; English et al., 2022). Once certified, the final phase delivers fuel to airport tanks for distribution via the hydrant system or refueler trucks.

Much of the existing research on supply chains focuses on the instability of feedstock availability due to the temporal and spatial variability of biomass yield and quality, along with uncertainties in pretreatment (Roni et al., 2023; Ma et al., 2022; Doliente et al., 2020). Some studies also address geopolitical implications (e.g., Shehab et al., 2023) and the scalability of technological pathways. Furthermore, research investigates the e-kerosene supply chain, which involves transporting captured CO2 through pipelines and other modalities (Engelmann et al., 2024; Ying et al., 2023). However, the operational and infrastructural impacts of these supply chains, beyond feedstock sourcing and biorefinery, are insufficiently researched and analysed (Babuder et al., 2024).

The current research has not fully investigated the multiple stakeholders in the supply chain, despite the fact that the production and adoption of SAF hinge on concerted cooperation across this chain. According to IATA on sustainability and economics, there are eight stakeholders in the supply chain, six of which are closely related to aviation, while one represents government/regulators, and the other is an international organisation/agency (IATA, 2023a; IATA, 2023b).

The stakeholders most closely related to aviation include feedstock producers, who are responsible for increasing feedstock production capacity and exploring additional feedstock options, and fuel producers, tasked with boosting SAF production capacity and developing next-generation technologies (Emmanouilidou et al., 2023; Tanzil et al., 2021). The roles of feedstock producers and fuel producers may not have clearly defined boundaries, as the production technology and feedstocks are closely intertwined; they must be compatible, or else they will be ineffective. The third stakeholder group comprises airframe and engine original equipment manufacturers, who are responsible for developing airframes and engines suitable for SAF and supporting testing (Heyne et al., 2021; Gan et al., 2023). Other stakeholders include airlines, which are the direct users of SAF. They are tasked with investing in feedstock and fuel producers by sending clear market signals and signing offtake agreements. End customers, whether corporate or individual air passengers, also play a role by contributing to the demand for SAF. Airports are another crucial stakeholder, ensuring that infrastructure is conducive for all suppliers to deliver their products to airlines, thereby creating a level playing field for all suppliers (not excluding any supplier) (Chao et al., 2019; Zhang et al., 2020; Jain et al., 2021). Government and local regulators play significant roles in ensuring that the supply chain runs smoothly and addressing any market failures through policy instruments. Lastly, international organisations/agencies advocate for and facilitate collaboration among regulators across jurisdictions, particularly for long-haul international flights (Ng et al., 2021; Pavlenko and Searle, 2021).

4.5. Policy interventions

Dodd and Yengin (2021) identified a deadlock among airlines, fuel producers, and governments, as each has different priorities. Airlines hesitate to invest unless SAF becomes more affordable and readily available, while SAF producers are reluctant without a guaranteed market from airlines. Consequently, governments play a crucial role in breaking this deadlock. The estimated investment required over a 27-year period, from 2023 to 2050, amounts to US$5.3 trillion (IATA, 2023b). Redirecting subsidies currently allocated to fossil fuels could contribute nearly one-third of this funding, as governments spend an average of US$55.6 billion per year on such subsidies (ATAG, 2021; IATA, 2023a). The UK has implemented the JetZero strategy, aiming to have five commercial-scale SAF plants under construction by 2025, with GBP 180 million in new funding (UK Parliament, 2023). Other countries should act quickly to establish similar SAF schemes to support the industry (Barbarà and Ennison, 2023; FAA, 2024; Mission Possible Partnership, 2022; Qantas Airways Limited, 2024).

Command-and-control regulations can effectively address environmental issues arising from market failures. A mandate for a certain percentage of SAF in jet fuel is easy to monitor and enforce, providing predictable carbon reduction and certainty. The EU leads by imposing quotas requiring fuel suppliers to blend 2% of SAF by 2025, 5% by 2030, and at least 63% by 2050 at all EU airports (CAPA, 2023b). A similar mandate has been imposed on airlines departing from Singapore (The Straits Times, 2024a).

Policy interventions, in the form of regulations and incentives, are crucial for enabling fuel suppliers to manage funding, financing, and risk mitigation. Incentives, such as SAF blender tax credits, can increase fuel yield, and stacking them reduces the probability of financial loss (Martinez-Valencia et al., 2023). Additional subsidies and combined federal and local programmes can significantly lower the minimum selling price (Brandt et al., 2022) and enhance the financial performance and assessed value of fuel suppliers (Weibel, 2018; Bhatt et al., 2023). Carlson et al. (2023) noted that variable subsidies, aligned with changing crude oil prices, may be more efficient and effective than fixed

subsidies per unit of SAF, allowing biorefineries to expand capacity.

Policies on SAF have been considered and discussed at multiple levels. At the macro level, researchers have focused on the role of the ICAO and the CORISA, advocating for a coherent global policy framework due to the transboundary nature of the aviation industry (Dodd and Yengin, 2021; Kania et al., 2023). Researchers have also proposed various approaches to accelerate the ASTM evaluation process, such as analysing low-cost SAF screening tools by combining timescale theory with reduced-order fuel properties and random forest regressions (Peiffer et al., 2019), and using a fuel properties database to streamline the approval process by addressing the physicochemical variability of SAF (Boehm et al., 2021; Heyne et al., 2021; Oldani, 2022). At the meso level, different countries and regions employ various policy approaches, such as pro-mandatory quotas (Chen et al., 2023), pro-carbon trading (Hamdan et al., 2022), and welfare-oriented policies (Jiang and Yang, 2021). However, Bullerdiek et al. (2021) cautioned that mandating airlines to use specific types of SAF may promote a broader range of technological pathways, but overly ambitious SAF blending targets could lead to a 'lock-in effect,' resulting in an oligopolistic market structure and excessive pricing power, thereby hindering other nascent innovations. Building on the policy discussions around carbon taxes and quotas (Chao et al., 2019; Jiang and Yang, 2021) and other relevant prior research, Zheng et al. (2024) utilised economic modelling to compare the effects of subsidies and quotas on SAF usage. This research found that while subsidy policies lead to higher SAF usage, greater consumer surplus, and increased airline profits, they also result in higher total emissions. This SAF policy model is sensitive to production costs and market potential, suggesting that policymakers should adjust strategies according to different scenarios. Chen et al. (2024) further develop the modelling and apply game-theoretic techniques to examine the effects of a government-mandated SAF on full-service carriers and low-cost carriers. The study demonstrates that the SAF mandate benefits LCCs, as they gain from enhanced fuel efficiency. When LCCs' fuel efficiency is sufficiently high, the SAF mandate can increase both their traffic and profits. At the micro level, research centres on airlines' reluctance to adopt SAF due to concerns about losing price competitiveness, as passengers may be unwilling to pay extra for carbon-neutral flights despite their positive perceptions of SAF's benefits (Xu et al., 2022).

5. Future research directions

After reviewing five key thematic topics, the following future directions (1–7) are inspired by the thematic discussions.

1). Inspired by section 4.1: Research in this area requires a solid foundation in chemical engineering, which can serve as prerequisite knowledge for social science and quantitative researchers. Regulatory concerns remain a significant topic. As global demand for biomass increases, proper regulation and certification are essential. Researchers should be mindful of the potential negative impacts of SAF production on the environment. For instance, in the U.S., ethanol producers seeking government subsidies must adhere to stringent criteria (Douglas and Renshaw, 2024). The European Union has also been cautious about the use of palm oil, a stance supported by the World Trade Organization (The Straits Times, 2024b).

2). Inspired by section 4.2: Understanding decarbonisation scenarios without SAF in place across jurisdictions is crucial. Currently, only SAF quota scenarios for certain flights have been simulated. Given that the SAF usage rate for commercial aviation is less than 0.1% as of 2024, real-world data are insufficient. Therefore, simulations can serve as valuable references for policymakers and businesses to validate the necessity of SAF. Research should also focus on the impacts of SAF adoption on airline competition and related industries, such as tourism and agriculture. Beyond merely comparing policies, theoretical modelling and numerical experiments (which will require quantitative data) could better inform policymakers.

3). Inspired by section 4.3: If governments continue to send strong market signals, more production units will be established, attracting interest from financial institutions and investment banks. Engineering economic analyses are needed to understand cost-benefit scenarios, including break-even points and internal rates of return (IRR). More techno-economic studies should examine investing in production units using different combinations of pathways and feedstocks.

4). Inspired by section 4.4: The dynamics between various stakeholders, such as farmers, logistics agencies, and regulatory bodies, remain underexplored. For example, the relationship between feedstock producers and biorefineries has not been thoroughly investigated, nor has the motivation for farmers to cultivate oil plants. Llimited research exists on how related industries manage risks while ensuring regulatory compliance (Babuder et al., 2024). Decarbonisation efforts will also necessitate new skills for existing and emerging roles in the aviation sector, with significant investments in Australia aimed at a production target of 20 GL per year, potentially creating long-term employment for around 250,000 people in regional areas (ARENA, 2019).

5). Inspired by section 4.5: More attention should be paid to international collaboration in promoting SAF production and adoption, particularly for long-haul international routes that contribute significantly to emissions but often fall outside regulations. Investigating international treaties and agreements between jurisdictions is essential for understanding their real impacts. Comparative analyses of various policies across jurisdictions and over time are also needed (Gössling and Lyle, 2021; Watson et al., 2024). As discussed in the second point of this section, economic modelling research can provide a broad comparison of policies across jurisdictions but offers deeper insights when using numerical data from specific jurisdictions (Zheng et al., 2024). In particular, a comprehensive global SAF dataset is still not available for the research.

6). Research efforts can extend beyond airlines to examine whether airline alliances facilitate greater SAF uptake. And understanding the extent to which passengers influence airlines' adoption of SAF is critical. Studies should investigate whether promotional materials can raise public awareness and willingness to pay higher fares for SAF-powered flights.

7). Greater attention could be paid to grey literature, which is often more timely and business-driven than journal articles. This grey literature approaches SAF from various angles, including technical certification, sustainability certification, technological analysis, prediction, and policy considerations. Reports from prominent international organisations such as ICAO, IATA, the International Energy Agency (IEA), and think tanks like the International Council on Clean Transportation (ICCT) and the World Economic Forum (WEF) are essential. The Industrial Alliance Air Transport Action Group (ATAG) and Airlines for Australia and New Zealand (A4ANZ) have also published relevant findings. Consulting firms like Deloitte and Kearney, along with

active regulatory bodies such as the UK Jet Zero Council, U.S. Federal Aviation Administration (FAA), the European Union Aviation Safety Agency (EASA), and the Australian Civil Aviation Safety Authority (CASA), as well as fuel suppliers like Air BP and Shell, have contributed valuable insights over the past three years. Reports on SAF have also been released by manufacturers such as Airbus and Boeing. The latter has introduced the Cascade Climate Impact Model to inform the public and researchers about advancements in this area. The abundant sources of grey literature require more academic attention; qualitative policy comparison studies and natural language processing could be effective approaches (Dimitriadou and Lavinsky, 2022; Douglas and Renshaw, 2024; Ember, 2024).

6. Conclusion

Aviation decarbonisation requires joint efforts, including market-based mechanisms (such as emissions trading schemes and carbon taxes), optimised air traffic management, aircraft design, and improvements in operational efficiency. Although it is not a silver bullet, SAF is a significant contributor to this effort.

This bibliometric analysis and literature review of articles on SAF from the past decade, primarily within the social sciences and quantitative disciplines, reveals that the aviation industry's approach to SAF should not be framed as a yes-or-no question. Instead, the focus should be on determining the appropriate percentage of SAF to use and the policies that should be implemented. Non-SAF alternatives alone will not achieve net-zero emissions by 2050, as discussed in Sections 4.1 and 4.2. In particular, electric and liquefied hydrogen-powered jets are unlikely to be commercially viable for mid- and long-haul flights until at least 2050, barring disruptive technologies (ATAG, 2021; Bain and Company, 2023). SAF remains the only commercially mature option available today, although pathways such as HEFA, Fischer-Tropsch, and AtJ are constrained by feedstock availability, as outlined in Section 4.3 (ATAG, 2023). The power-to-liquid pathway shows promise for the future but requires further research and development to scale up renewable hydrogen production. While production has received overwhelming academic interest, ensuring seamless delivery to aircraft necessitates more coordination across the entire supply chain, as discussed in Section 4.4.

Most importantly, as outlined in Section 4.5, governments and international organisations must agree on effective policies and regulations to ensure the participation of all airlines and create a level playing field globally. Inter-continental ultra-long-haul flights contribute significantly to carbon emissions and should be prioritised. Mandatory regulations may have flexible timelines for less developed countries and airlines. Incentive-driven policies could facilitate early production and adoption through various packages and nudges. A firm commitment to the net-zero goal through SAF from all governments would send a strong signal to investors, producers, and airlines, emphasising the importance of acting early.

This study combines bibliometric analysis with a systematic literature review, but it has limitations, primarily due to the reliance on datasets such as Scopus and the Web of Science Core Collection. These datasets are comprehensive and widely recognised within academia, but they may not fully capture grey literature. As the SAF sector has developed rapidly, particularly over the last three years, there has been a surge in industrial reports, media coverage, and conference proceedings. Secondly, this review may therefore exclude relevant studies due to the strict inclusion and exclusion criteria imposed by these databases, potentially missing some emerging interdisciplinary perspectives. Moreover, citation bias can skew the evaluation of research quality, as older papers tend to receive more citations than newer ones. For instance, a paper published five years ago will typically have more visibility and citations than one published just two or three months ago.

Despite these minor limitations, this review identifies seven key areas for future research in SAF. It also encourages non-engineering researchers to engage with SAF research, contributing via theoretical modelling or empirical studies. This study also advocates for more research on SAF, particularly using existing ADS-B or OAG datasets, case studies, grey literature and the involvement of researchers from diverse disciplines to advance aviation decarbonisation.

CRediT authorship contribution statement

Yuchao Xu: Writing – original draft, Methodology, Formal analysis. **Yahua Zhang:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Xin Deng:** Writing – review & editing, Supervision. **Seung-Yong Lee:** Writing – review & editing, Supervision. **Kun Wang:** Writing – review & editing, Conceptualization. **Linbo Li:** Writing – review & editing, Supervision.

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Appendix 1. Uncertified SAF pathways under consideration

Technology	Feedstocks	Final Products	Direct Blend-in?	Key features	Source
Direct liquefaction	Coal, biomass	Synthetic crude oil/ Bio crude oil	No	Using high pressure and temperature without oxygen to convert solid feedstocks into liquid SAF	Krogh et al. (2022)
Power-to-X (PtX)	Electricity	Various, including hydrogen, methane, liquid fuels, and chemicals	No	Converting electricity into other forms of energy, substances, or materials.	(Fasihi et al., 2017; Krogh et al., 2022; Melo et al., 2020)
Gas-to-Liquid	Natural gas or other gaseous hydrocarbons	Liquid hydrocarbons	No	Syngas production through steam methane reforming or partial oxidation, followed by Fischer-Tropsch synthesis or methanol synthesis to produce liquid fuels.	(Heesterman, 2019; Krogh et al., 2022)
Integrated carbonisation-gasification-Fischer–Tropsch (ICGFT)	Coal, biomass	Synthetic liquid fuels	No	Enhancing Fischer–Tropsch by integrating carbonisation and gasification into a more efficient and more environmentally friendly single process.	Tanzil et al. (2021)

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Technology	Feedstocks	Final Products	Direct Blend-in?	Key features	Source
Volatile fatty acids fermentation (VFA-SAF)	Organic waste, wastewater	Short-chain volatile fatty acids	No	Using fermentation of organic waste to produce VFAs	Huq et al. (2021)
Power to Liquid (PtL) kerosene	Electricity, water, CO2	Synthetic liquid fuels (Kerosene)	Yes	The subset of PtX. Involves electrolysis to produce hydrogen from water, which is then combined with CO2 in a synthesis process (e.g., Fischer-Tropsch) to produce synthetic kerosene for aviation.	(Dietrich et al., 2024; Fasihi et al., 2017; Hasan et al., 2021; Melo et al., 2020; Micheli et al., 2022; Ozkan et al., 2024; Shehab et al., 2023; Stauch and Müller, 2022)
Gasification and Fischer-Tropsch process (GFT)	Coal, biomass, or waste	Synthetic liquid fuels	No	Converting solid or liquid feedstocks into syngas, which is then transformed into longer-chain hydrocarbons via Fischer-Tropsch synthesis to produce liquid fuels.	(Okolie et al., 2023; Tanzil et al., 2021)
Direct sugar to hydrocarbon (DSHC)	Sugars from biomass	Synthetic liquid fuels	No	Converting sugars into hydrocarbons through biochemical and/or chemical processes, without the need for intermediate fermentation to ethanol.	(Melo et al., 2020; Okolie et al., 2023; Tanzil et al., 2021)
Fast pyrolysis (FP)	Biomass	Bio crude oil, char, syngas	No	Rapid heating of biomass without oxygen to produce bio-oil, which can be upgraded to fuels or chemicals, as well as char and syngas as by-products.	(Krogh et al., 2022; Okolie et al., 2023; Siegfried et al., 2023; Tanzil et al., 2021)
Aqueous phase reforming (APR)	Water-soluble biomass components (e.g., sugars, alcohols)	Gases, liquid hydrocarbons	No	Transforming aqueous streams of biomass-derived compounds into hydrogen and other valuable chemicals through a catalytic process at moderate temperatures with high pressure.	(Okolie et al., 2023; Pipitone et al., 2023; Zhu et al., 2022)
hydrothermal liquefaction (HTL)	Wet biomass, algae	Bio crude oil	No	Using high pressure and temperature in a water medium to convert wet biomass into biocrude.	(Huq et al., 2021; Krogh et al., 2022; Melo et al., 2020; Okolie et al., 2023; Zhu et al., 2022)

Appendix 2. Research methods of selected articles

Research Methods	Authors
Modelling and simulation, Scenarios analysis	(Ahmad et al., 2021; Alam and Dwivedi, 2019; Aygun and Caliskan, 2022a; Chen et al., 2023; Cican et al., 2023; Field et al., 2022; Gautam et al., 2023a; Gössling and Humpe, 2023; Gunaltili et al., 2023; Huang et al., 2023; Isufaj et al., 2022; Jain et al., 2021; Jiang and Yang, 2021; Kito et al., 2023; Krogh et al., 2022; Li and Merkert, 2023; Liu et al., 2021; Ma et al., 2022; Male et al., 2021; Mousavi-Avval et al., 2023; Ng, 2023; Phippen et al., 2022; Prasannakumar et al., 2022; Roni et al., 2023; Shehab et al., 2023; Siegfried et al., 2023; Sobieralski, 2023; Tian et al., 2020; Timmons and Terwel, 2022; Uludere Aragon et al., 2023; Ying et al., 2023; Zheng et al., 2024)
Life cycle assessment	(Keiser et al., 2023; Kossarev et al., 2023; Melo et al., 2020; Micheli et al., 2022; Puschnigg et al., 2023; Rupcic et al., 2023; Taheripour et al., 2022; Vásquez et al., 2019; Wang & Sun et al., 2023; Zhu et al., 2022)
Bibliometric analysis	(Gössling and Dolnicar, 2023; Gössling and Lyle, 2021; Hopkins et al., 2023; Keiser et al., 2023; Leal Filho et al., 2023; Lu et al., 2023; Rijo et al., 2023; Su et al., 2022)
Techno-economic assessment	(Brandt et al., 2022; Collis et al., 2022; Dietrich et al., 2024; English et al., 2022; Kossarev et al., 2023; Pipitone et al., 2023; Trejo-Pech et al., 2021b)
Monte Carlo simulation	(Carlson et al., 2023; Kadyk et al., 2019; Kılkış and Kılkış, 2017; Pipitone et al., 2023)
Financial analysis	(Carlson et al., 2023; Collis et al., 2022; Mahtani and Garg, 2018; Martinez-Valencia et al., 2023)
Survey & case study	(Ahmad and Xu, 2021; Dodd and Yengin, 2021; Engelmann et al., 2020; Kania et al., 2023; Korkut and Fowler, 2021; McCollum et al., 2021; Moo et al., 2022; Oldani et al., 2022; Sharma et al., 2021; Xu et al., 2022; Yilmaz and Kose, 2021; Zhang et al., 2022)

Appendix 3. Research themes and corresponding articles

Research Themes	Authors
Sustainable certification of pathways and feedstocks	(Ahmad et al., 2021; Afonso et al., 2021; Barros Pintos et al., 2023; Bergero et al., 2023; Carlson et al., 2023; Centracchio et al., 2018; Collis et al., 2022; Cooke and Bernheim, 2022; Cosgrove, 2018; Gao et al., 2022; Gunaltili et al., 2023; Guo and Huang, 2021; Hamdan et al., 2022; Heyes et al., 2020; Ho-Huu et al., 2019; Huang et al., 2023; Jain et al., 2021; Jiang et al., 2022; Kito et al., 2023; Krogh et al., 2022; Kwasiborska and Skorupski, 2021; Lazic et al., 2023; Leavitt et al., 2018; Liu et al., 2021; Liu et al., 2023; Male et al., 2021; Ng, 2023; Okolie et al., 2023; Oldani et al., 2022; Prasannakumar et al., 2022; Sharma et al., 2021; Sobieralski, 2023; Xue et al., 2020; Zhang et al., 2022; Zhu et al., 2022.)
Economic simulation of alternative solutions	(Alam and Dwivedi, 2019; Bach et al., 2021; Baidoo et al., 2022; Cican et al., 2023; English et al., 2022; Fasihi et al., 2017; Field et al., 2022; Gautam et al., 2023; Heesterman, 2019; Huq et al., 2021; Karami et al., 2022; Kossarev et al., 2023; Krogh et al., 2022; Male et al., 2021; Micheli et al., 2022; Mousavi-Avval et al., 2023; Phippen et al., 2022; Pipitone et al., 2023; Puschnigg et al., 2023; Ranucci et al., 2018; Roni et al., 2023; Shehab et al., 2023; Siegfried et al., 2023; Taheripour et al., 2022; Uludere Aragon et al., 2023; Vásquez et al., 2019; Wang & Guo et al., 2023; Ying et al., 2023; Yusaf et al., 2022)
Economic feasibility of pathways and feedstocks	(Aygun and Caliskan, 2022; Boehm et al., 2021; Brandt et al., 2022; Caraveo Gomez Llanos et al., 2023; Chen et al., 2017, 2023; Collis et al., 2022; Doliente et al., 2020; English et al., 2022; Farid and Donyatalab, 2022; Gössling and Humpe, 2023; Kramer et al., 2022; Landera et al., 2022; Liu et al., 2022; Ma et al., 2022; Martinez-Valencia et al., 2023; McCollum et al., 2021; Moo et al., 2022; Singh et al., 2019; Su et al., 2022; Tanzil et al., 2021; Trejo-Pech et al., 2021; Wu and Yang, 2021; Zhang et al., 2018)

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Research Themes	Authors
Supply chain dynamics and involvement of multiple stakeholders	(Ahmad and Xu, 2021; Dube and Nhamo, 2019; Gössling and Dolnicar, 2023; Hopkins et al., 2023; Kito et al., 2023; Leal Filho et al., 2023; Li and Merkert, 2023; McCollum et al., 2021; Xu et al., 2022)
Policy interventions	(Abrantes et al., 2021; Ahmad, 2018; Barrett and Caldera-Petit, 2021; Bartle et al., 2021; Bullerdiek et al., 2021; Chao et al., 2019; Darda et al., 2019; Dodd and Yengin, 2021; García-Olivares et al., 2020; Gössling and Lyle, 2021; Hasan et al., 2021; Hassan et al., 2018; Jiang and Yang, 2021; Kania et al., 2023; Korkut and Fowler, 2021; Littorin, 2021; Rumizen, 2021; Smith et al., 2017; Villegas Díaz et al., 2020; Zaporozhets et al., 2021)

Data availability

Data will be made available on request.

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